Abstract

Numerical modeling of a turbulent boundary layer on wavy and irregular surfaces

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This dissertation is devoted to the passive control of the turbulent boundary layer (TBL) through the design and optimization of surface waviness. It follows a structured approach based on five research papers (Papers 1–5) and one preprint (Paper 6). Two fields of surface waviness application are explored: aerodynamics and heat transfer. The primary focus is aerodynamics, specifically mitigating TBL separation, which is promoted by an adverse pressure gradient (APG) and occurs when the wall shear stress reaches τ_w=0. TBL separation is a fundamental problem in aerodynamic applications, leading to increased drag and reduced energy efficiency. Historically, numerous passive flow control methods, which influence TBL without external energy input, have been employed to mitigate separation. Among these, wavy wall (WW), being the research object of this dissertation, has emerged as a promising solution.

Four research papers (Papers 1–4) are devoted to the control of TBL separation, presenting a logical progression of the investigation. In the first stage (Paper 1), LES method is employed to examine APG and zero pressure gradient (ZPG) flows over flat and wavy surfaces, with a detailed focus on near-wall flow physics. The numerical domain is a cuboid and represents a simplification of the real-flow setup, with pressure gradients imposed via boundary conditions. In this configuration, due to the insufficient length of the domain, the detachment of TBL is not observed. Hence, the conclusions regarding TBL separation control are drawn based on changes in τ_w, assuming that its increase indicates a delay in TBL separation. The LES results, validated against experimental data, show that a two-dimensional sinusoidal WW enhances τ_w. Furthermore, it is found that the global pressure gradient strongly influences both the effectiveness of WW in modifying τ_w and the flow structures that form over WW. A subsequent parametric analysis (Paper 2) explores the influence of WW amplitude (A) and wavelength (λ) on τ_w. The results indicate that both variables critically impact τ_w, enabling either its increase or reduction relative to the reference configuration. An optimal combination of A and λ is identified, which enhances τ_w significantly compared to the reference design. Building on these findings, a refinement is introduced by incorporating a streamwise or

counter-streamwise tilt into the WW design (Paper 3). This modification, which addresses limitations observed in previous studies, ensures an increase in τ_w by 70% compared to the best-performing sinusoidal WW from Paper 2. Moreover, the new configuration eliminates flow separation in the troughs of WW, thereby reducing the total drag coefficient C_d by 14%. The final stage of the part devoted to aerodynamics (Paper 4) extends this research by evaluating the performance of WW in a more realistic scenario, i.e. where it is embedded into an airfoil-type surface, enabling direct investigation of the separation region, which was not possible in Papers 1-3. It is shown that, in this configuration, WW retains its ability to enhance τ_w. Moreover, a downstream shift of the separation point is observed, confirming the conclusions from previous studies (Papers 1–3). Furthermore, a Reynolds number (*Re*) sensitivity analysis reveals that the effectiveness of WW is strongly dependent on the inflow conditions, with its performance diminishing as *Re* decreases.

Motivated by the promising achievements in controlling flow separation by WW, its application is extended to enhance heat transfer (Papers 5 and 6). Specifically, the shape of a heated WW section of a channel and of a pipe is optimized. This analysis is particularly relevant for practical applications, since these constitute fundamental components of compact heat exchangers, where wall geometry critically impacts the flow. The objective is to identify a WW configuration that ensures maximal temperature uniformity with minimal losses due to pressure drop. The optimization procedure employs an element of machine learning, the Bayesian optimization method, and combines it with flow simulations and researcher intuition (human-assisted optimization). Consequently, by strategically designing the surface of either the pipe or channel, the thermal-hydraulic efficiency can be significantly altered. For the pipe, the optimal WW shape features two outward-oriented cavities leading approximately threefold reduction in the temperature variance at insignificant rise in the pressure drop. For the channel, the optimal shape is characterized by a progressively increasing WW amplitude. Depending on the number of parameters defining the WW shape, e.g., number of waviness periods, the observed temperature variance can be reduced up to approximately 62 times, with a moderate pressure drop. The optimal and nearly optimal WW shapes promote recirculation within the cavities, which enhances fluid mixing and augments heat transfer from the wall to the core of the flow, while maintaining minimal pressure losses.